REPORT

SPECTRAL WIND LOADS IN AQUASIM

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Summary:

This document describes how wind loads are implemented to AquaSim including spectral wind loading.

The document describes two spectral formulations to wind that may be applied. Spectral wind load generation can be applied from NORSOK wind spectrum formulation with gust wind in the same direction as the mean wind or it can be applied with N400 formulation where gusts also transverse gust is included.

The spectral wind loads are implemented in a manner such that the user may adjust to any desired combination of spectral wind by manipulating each wind period component and vertical relation.

Some cases are presented to validate the AquaSim wind calculations.

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1. INTRODUCTION

This report presents the possibility to introduce wind loads with gust to AquaSim. Spectral wind load generation can be applied from NORSOK (2016) wind spectrum formulation with gust wind in the same direction as the mean wind or it can be applied with N400 (2015) formulation where gusts also transverse gust is included.

The NORSOK formulation follows NORSOK N003 (2016) Section 6.4 pp 30-32. The N400 (2015) formulation follows the formulation described in Section 5.4.3 from pp 62.

2. WIND LOADS

The wind load consists of a mean wind load which varies with height above water and return period. Input to AquaSim is 10 min mean wind 10 meters above water surface/ground.

Mean 10 min wind and harmonic wind components may be generated based on spectral formulations (NORSOK or N400), then may be manipulated to fit any desired formulation.

2.1. Wind profiles according to NORSOK

2.1.1. Mean wind

Define a coordinate system where the z- axis points vertically upwards with the origin at the mean free surface of the water line. Wind direction of 0^o DEG means the wind is blowing along the local x- axis and 90^o DEG means the wind is blowing along the local y- axis. NORSOK propose the following relation between mean 10 min wind velocity 10 meters above the mean water line and mean wind with other return periods at other z- locations by:

$$u(z,t) = U(z)\left(1 - 0.41 I_u(z)\ln\left(\frac{t}{t_0}\right)\right)$$

Equation 1

For a vertical location z- the wind velocity can be described as

$$U(z) = U_0\left(1 + \mathrm{C}\ln\left(\frac{z}{10}\right)\right)$$

Equation 2 NORSOK

Where $U(z)$ is the 1-hour average wind velocity. U_0 is the velocity at $z_0 = 10\ m$.

$$C = \frac{5.73}{100}(1 + 0.15U_0)^{0.5}$$

and

$$I_u(z) = 0.06(1 + 0.043U_0)\left(\frac{z}{10}\right)^{-0.22}$$

U_0 (m/s) is the 1-hour mean wind speed at 10 m.

The relation between U_0 for 1 hour ($U_{0\,(1h)}$) and U_{010min} can be derived by

$$U_{010min} = U_{0\,(1h)}\left(1 - 0.41 I_{u\,(z=10)} \ln\left(\frac{t}{t_0}\right)\right)$$

Equation 3

In NS 9415, U_{010min} is the basis such that Equation 3 is used the other way around.

2.1.2. Wind gust

In AquaSim, if wind gust according to NORSOK N003 is applied, the spectral distribution of the harmonics of the varying part on wind velocity is found by:

$$S(f) = 320\frac{\left(\frac{U_0}{10}\right)^2\left(\frac{z}{10}\right)^{0.45}}{\left(1 + \tilde{f}^n\right)^{\frac{5}{3n}}}$$

Equation 4 Spectral value NORSOK

where $n = 0.468$.

$$\tilde{f} = 172\, f * \left(\frac{z}{10}\right)^{\frac{2}{3}}\left(\frac{U_0}{10}\right)^{-0.75}$$

Equation 5

2.2. Wind profiles according to N400

2.2.1. Mean wind

Mean wind according to N400 is found from:

$$U(z) = U_b K_r \ \ln\left(\frac{z}{z_0}\right)$$

Equation 6 N400

U_b is the base value for wind velocity, U.

$$K_r = 0.19\left(\frac{z_0}{z_{0,2}}\right)^{0.07}$$

Equation 7

$z_{0,2}$ refer to z_0 in terrain category 2 in Table 1. Values for z_0 is found from EN 1991-1-4 (2005), Table 4.1 which data is given in Table 1.

Table 1

Terrain Category	**Simplified explanation**	z_0	U_0/U_b
0	Open sea	0.003	1.27
1	Lakes, fjords, flat area	0.01	1.17
2	Some obstacles	0.05	1

Note: in AquaSim the mean wind at 10 meters height is given as input independent of terrain category. The base wind is found by the rightmost column in Table 1, then the wind at a vertical location, z is found from Equation 6.

2.2.2. Wind gust

In AquaSim, the wind gust specter according to N400(2015) is expressed as

$$S_u(f) = \frac{A_u\,\hat{f}_u {\sigma_u}^2}{f\left(1 + 1.5A_u\hat{f}_u\right)^{5/3}}$$

Equation 8 Spectral value N400

Where the value of A_u according to N400 is 6.8. The standard deviation is

$$\sigma_u = k_r v_b$$

Where k_r is given in Equation 7. The adjusted frequency $\hat{f}$ is given as

$$\hat{f}_u = \frac{fL_{xu}(z)}{v_m(z)}$$

Equation 9

Where f is the frequency. Note that L_{xu} in this document is the same as ${}^{x}L_u$ in N400 but a slightly different way to write is chosen in this document. The term means length in x direction applicable for wind component u which is the wind component in the x-direction. In general, u,v,w denotes wind in the x-,y- and z- direction respectively in an orthonormal coordinate system where the local x- axis in in the direction of the mean wind and the z axis points vertically upwards. According to N400 Eq. 5.2,

$$L_{xu}(z) = L_1(\frac{z}{z_1})^{0.3}$$

In N400 eq. 5.2, L_1 is set to 100 such that

$$L_{xu}(z) = 100(\frac{z}{z_1})^{0.3}$$

The adjusted frequency, $\hat{f}_u$ can then be written as:

$$\hat{f}_u = \frac{f * 100(\frac{z}{z_1})^{0.3}}{U_m(z)}$$

and then introducing from Equation 6:

$$\hat{f}_u = \frac{f * 100(\frac{z}{z_1})^{0.3}}{U_b K_r \ \ln\left(\frac{z}{z_0}\right)}$$

Equation 10

z_0 is seen in Table 1 and z_1 is *10 m* in N400. The N400 wind formulation also describes winds gusts transverse to the mean wind direction. The spectrum for horizontal component transverse to the mean wind direction is given as:

$$S_v(f) = \frac{A_v \ \hat{f}_v \sigma_v{}^2}{f\left(1 + 10.2\hat{f}_v\right)^{5/3}}$$

Equation 11 Spectral value horizontal wind gust transverse to mean wind direction

Where the value of A_v according to N400 is 10. The standard deviation for gust in the transverse direction is 75% of the gust in the same direction as the mean wind, i.e.:

$$\sigma_v = \frac{3}{4}\sigma_u$$

The adjusted frequency $\hat{f}_v$ is given as

$$\hat{f}_v = \frac{f L_{yv}(z)}{v_m(z)}$$

Where

$L_{yv}(z) = \frac{L_{xu}(z)}{4}$

According to N400, Eq. 5.3.

The vertical component transverse to the mean wind direction is given as:

$$S_w(f) = \frac{A_w \hat{f}_w {\sigma_w}^2}{f\left(1 + 10.2\hat{f}_w\right)^{5/3}}$$

Equation 12 Spectral value vertical wind gust

Where the value of A_w according to N400 is 10. The standard deviation for gust in the transverse direction is 25% of the gust in the same direction as the mean wind, i.e.:

$$\sigma_v = \frac{1}{4}\sigma_u$$

The adjusted frequency $\hat{f}_v$ is given as:

$$\hat{f}_w = \frac{f L_{zw}(z)}{v_m(z)}$$

Where

$L_{zw}(z) = \frac{L_{xu}(z)}{18}$

According to N400, Eq. 5.3.

2.2.3. Covariance

N400 have an equation describing the covariance in space of gust in all directions (N400 Eq. 5.6). The covariance spectrum:

$$\frac{Re\left[S_{i_1 i_2}(f, \Delta s_j\right]}{\sqrt{S_{i_1}(f) S_{i_2}(f)}} = \exp\left(-C_{ij} \frac{f \Delta S_j}{v_m(z)}\right)$$

Where ΔS_j is the horizontal or vertical distance between points and the other abbreviations are

$$i_1, i_2 = u, v, w$$

$$j = y, z$$

$$C_{uy}, C_{uz} = 10.0,\ C_{vy} = C_{vz} = C_{wy} = 6.5,\ C_{wz} = 3.0$$

Equation 13

2.3. Comparison of mean wind profiles

Figure 1 shows the mean wind, $U(z)$, as function of height for 4 wind profiles:

- NORSOK wind profile
- N400 and EN 1991-4 wind profile, terrain category 0
- N400 and EN 1991-4 wind profile, terrain category 1
- N400 and EN 1991-4 wind profile, terrain category 2

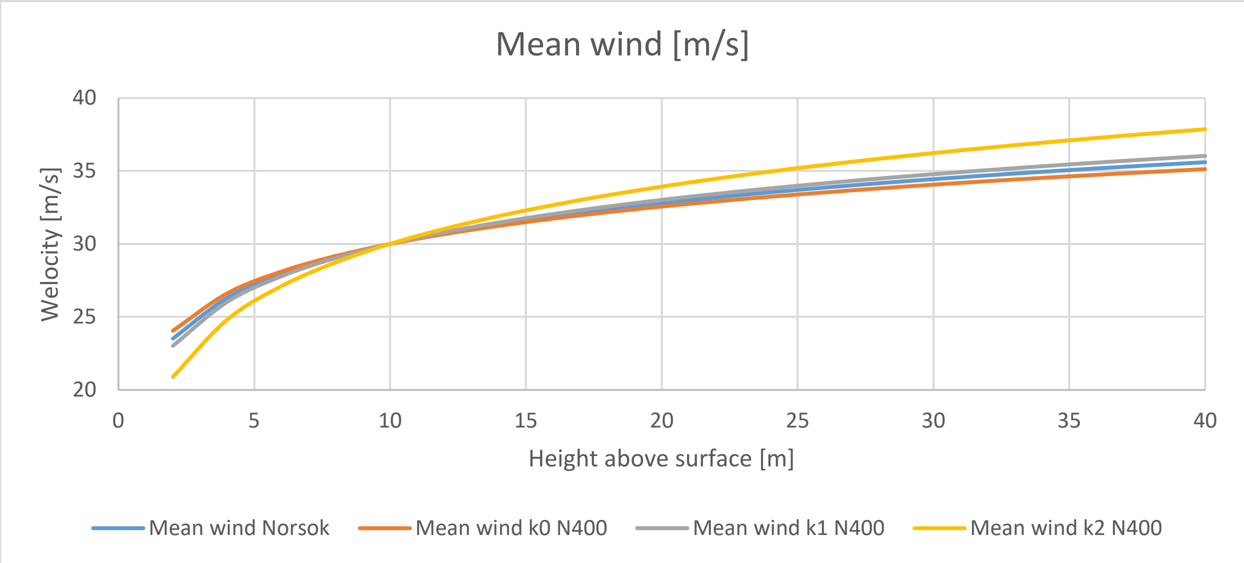

Figure 1 Mean wind velocity as function of height

As seen from Figure 1, the dependence between vertical location and mean wind velocity is very similar for the lines applicable for open water (NORSOK and k0 and k1). The only curve that is slightly different is the k2 which is more applicable for land.

2.4. Generation of wind time series

N number of sinusoidal components are chosen to represent the time varying wind component based on the spectral density.

The first period, T (=1/f) is chosen as 300 seconds corresponding to 5 minutes, then succeeding periods are found as n sinusoidal components, where:

$$T_{i+1} = T_i * PF1 - PF2$$

Where *PF1 = 0.955*(100/N)* and PF2 = *0.05*(100/N)*.

$$f_{i+1} = \frac{1}{T_{i+1}}$$

A sinusoidal wind component with amplitude A is then established as:

$$A_i = \sqrt{2 * S(f) * \Delta f}$$

Equation 14

Where i = 1,n and the time series for the irregular gust wind is described by N sinusoidal wind load components. The variance of the spectral wind velocity is found as

$$\int_0^{\infty} S(f)df = \sigma^2 = \sum_{i=1}^{N} \frac{{A_i}^2}{2}$$

where σ is the standard deviation of the process.

The average wind velocity has height dependence according to Equation 2. The different period-components of the wind gust have a different relation to the z-location relative to the reference height of 10 meters. Define *zrel* as z/z_0 where $z_0 = 10\ m$. For the NORSOK wind formulation, the dynamic part of each wave amplitude has the following z- variation:

$$A_i(z) = A_i(z0)\left(\frac{z}{z_0}\right)^{0.4+\frac{i}{3N}}$$

Equation 15

For the N400 wind formulation, the wind gust amplitude at z elevation different from 10 is linked to the gust at 10 meters through the relation in Equation 16.

$$A_i(z) = A_i(z0)\left(\frac{z}{z0}\right)^{-00.625+\frac{PM}{1.09}}$$

Equation 16

Where

$$PM = \max({T_i}^{0.023} - 1{,}0)$$

Equation 17

This means that NORSOK and N400 have slightly different relations for the amplitudes of the gusts in the *z*- direction. The *z*- variation in the analysis is a chosen fit to the formulations in the standards. The amplitude of each wind component is described by:

$$A_i(t) = A_i \sin(\omega_i t - k_1 x - k_2 y - k_3 z + \varepsilon_i)$$

Equation 18

Where $\omega_i = 2\pi/T_i = 2\pi f_i$ and ε_i is a random number between *0* and 2π. Each amplitude and *z*-variation is calculated in AquaEdit and can be manipulated manually. k_1, k_2 and k_3 in Equation 18 is found as:

$$k_{j,j=1,2,3} = C_{ij}\frac{f}{v_m(z)}$$

Where C_{ij} is found in Equation 13. *i* is wind directions *1-3*, *x*, *y* and *z*. The dynamic variation of the wind (the gust) is expressed as a sum of sinusoidal components. The expression in Equation 18 is carried out for three directions, parallel to the mean wind (local *x*- direction), perpendicular to the wind, horizontally (*y*-) and perpendicular to the wind, vertically (*z*-).

3. INPUT TO AQUASIM SOLVER

Wind data is given in a table in terms of sinusoidal wind components in N rows. For each wind component the following data is given:

- Amplitude: Amplitude of the sinusoidal wind component A_i.
- Periode: Period T_i of the wind component.
- KVERT: Vertical variation factor, where the relation is:

$$A_i(\mathrm{z}) = A_i(z0) * zrel^{KVERT}$$

Equation 19

Where *zrel* is equal z/z_0 where z_0 is *10 m.*

- Beta: Beta is the wave direction, Beta = *0* means wind along the *x*- axis and Beta = *90* means wind along the *y*- axis.
- Random: Random is a random number uniformly distributed between *0* and 2π as seen in Equation 18.

Note that a reference *10* min wind amplitude is used to generate the data for the wind spectrum (alternatively the user can specify *1* hour wind). If this wind is not the same as the static mean wind velocity given in the static wind velocity part of these wind, the static and the dynamic wind parts will not have the same basis and will be artificial. At the same time, it is possible for the user to manipulate wind input such that almost any combination can be modeled.

3.1. Activation of dynamic wind

To activate the use of wind spectrum, and hence wind gust in AquaSim, one must activate it to obtain the static wind distribution according to Equation 1. Further, the gust is described with N harmonic components (for NORSOK) and *3N* harmonic components (for N400).This is due to N400 prescribes wind gust in *3* directions, while NORSOK only prescribe 1 direction.

Wind can only be introduced to beam and truss components, and will be introduced to all such components over the mean water line. The loads from wind are then calculated in the same way as for current and wave using the Morison Equation. Density of the air is set to 1.27 kg/m^3. The cross-flow principle is applied in the same way as for components in water and components with lift can also be analyzed with wave loads.

4. VALIDATION

4.1. Case study 1, cantilever 10 meters above water

A case study has been established, a 10 meter long cantilever beam as seen in Figure 2.

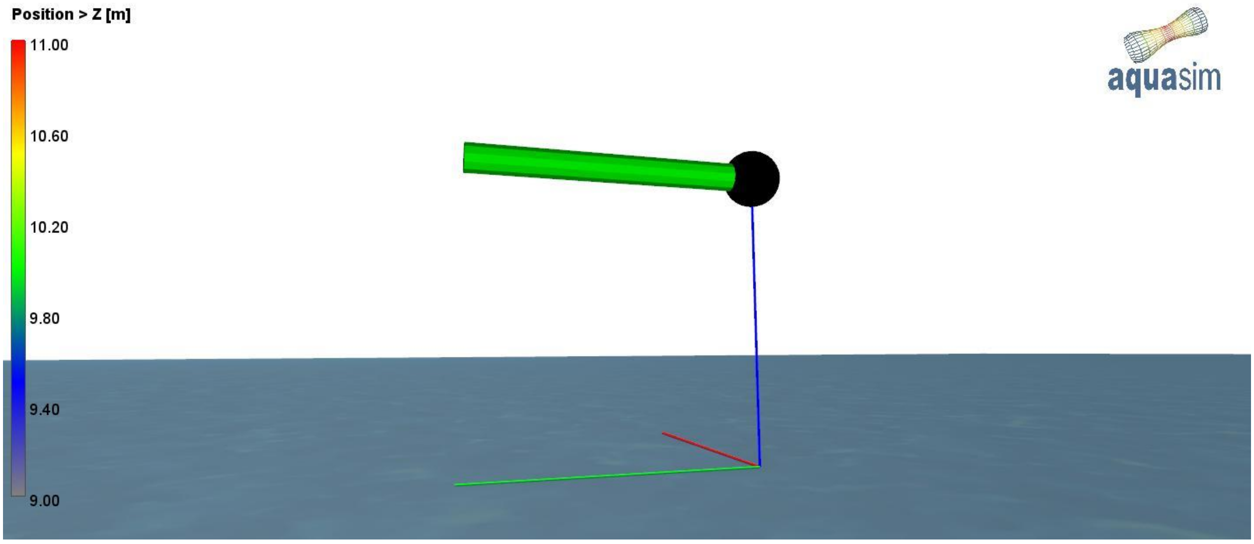

Figure 2 One element model, 10 m long cantilever at position z = 10.

4.1.1. Static mean wind load

Wind with a reference velocity of 30 m/s at 0 deg (along the x axis) is applied. The main particulars for the case are given in Table 2.

Table 2 Main data

Paramter	Value
Length [m]	10.00
Half length [m]	5.00
Diameter [m]	1.00
Cd	1.20
Rho air [kg/m3]	1.21
Wind velocity [m/s]	30.00

The shear force for an element reported in AquaSim is the average shear force, which at static equilibrium was found to be 3267 N as seen in Figure 3.

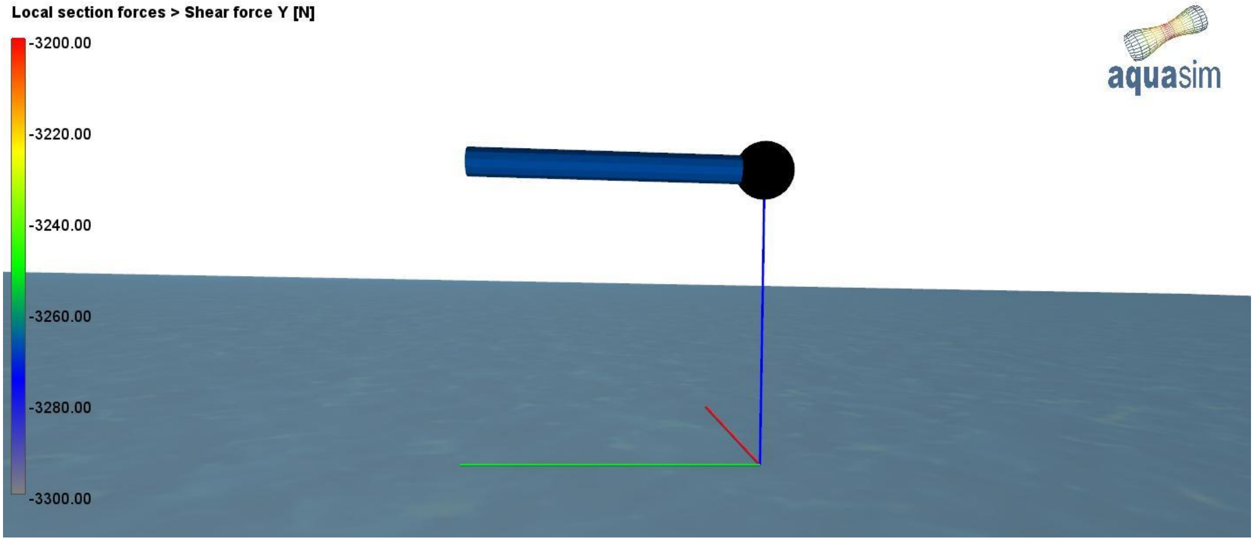

Figure 3 The shear force in the positive y-direction is calculated to 3267 N in static analysis with 30 m/s wind both for the formulations at NORSOK and N400

At the reference height both wind-formulations have results applicable for that given height. Methods are compared in Table 3 the results compare very well as they should.

Table 3 Results, analytic formulae compared with numeric in AquaSim

Method	Shear force [N]
Analytic	3267
Wind NORSOK (AquaSim)	3267
Wind N400 (AquaSim)	3267

Figure 4 shows shear force in beam as function of height based on analytic calculations compared to AquaSim calculations (Aquasim at 20 and 30 m height). As seen from the figure, results compare well.

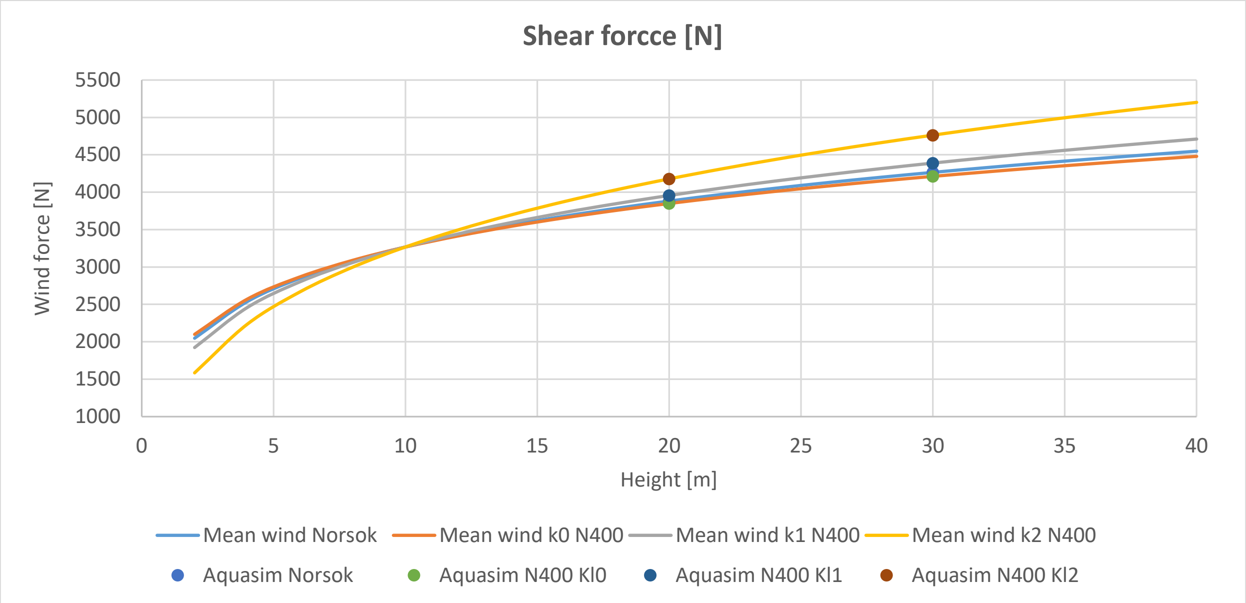

Figure 4 Shear force in beam

4.1.2. Dynamic wind basis

In the time domain analysis, the spectral wind is represented by a finite number of harmonic wind velocity components, these are generated by the AquaSim preprocessor and represents wind at 10 meters height. Both amplitudes, phases and z-dependencies can then be manipulated for possible better fit to measurements. Figure 5 shows the standard deviation of the wind gust for the following 3 cases:

- Analytic: Calculated directly from the integrated spectrum of the gust.
- AquaSim 100: Calculated from 100 sinusoidal component used to represent the spectrum.
- AquaSim 200: Calculated from 200 sinusoidal component used to represent the spectrum.

The four methods compared are NORSOK and N400 k0, k1 and k2.

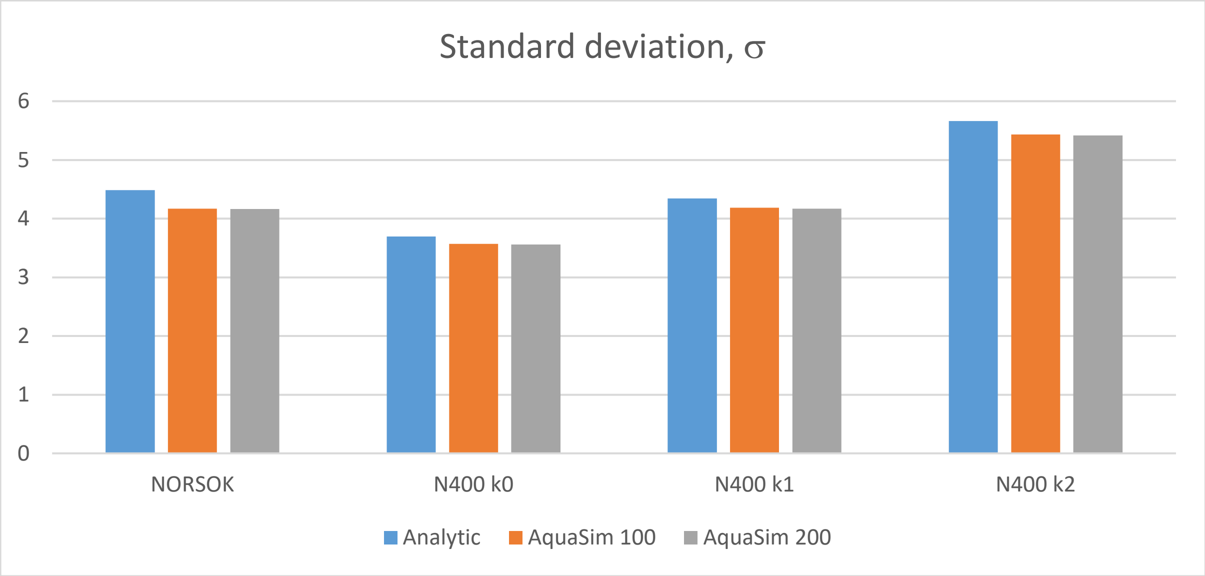

Figure 5 Standard deviations analytic results compared to finite representation

As seen from Figure 5 the standard deviation in the finite representation is slightly lower than in the integral of the spectrum. A closer look at this showed that the difference well could be explained by the fact that higher periods than 5 minutes are not used to represent the wind gust. There is also a cut-off for periods lower than 0.1 s.

The N400 formulations for wind also include horizontal and vertical gust transverse to the mean wind direction. Figure 6 shows the standard deviation of the sinusoidal components in AquaSim compared to analytical results:

- Parallel means gust in the same direction as the mean wind
- Transverse horizontal means gust horizontally transverse to the mean wind direction
- Transverse vertical means gust vertically transverse to the mean wind direction

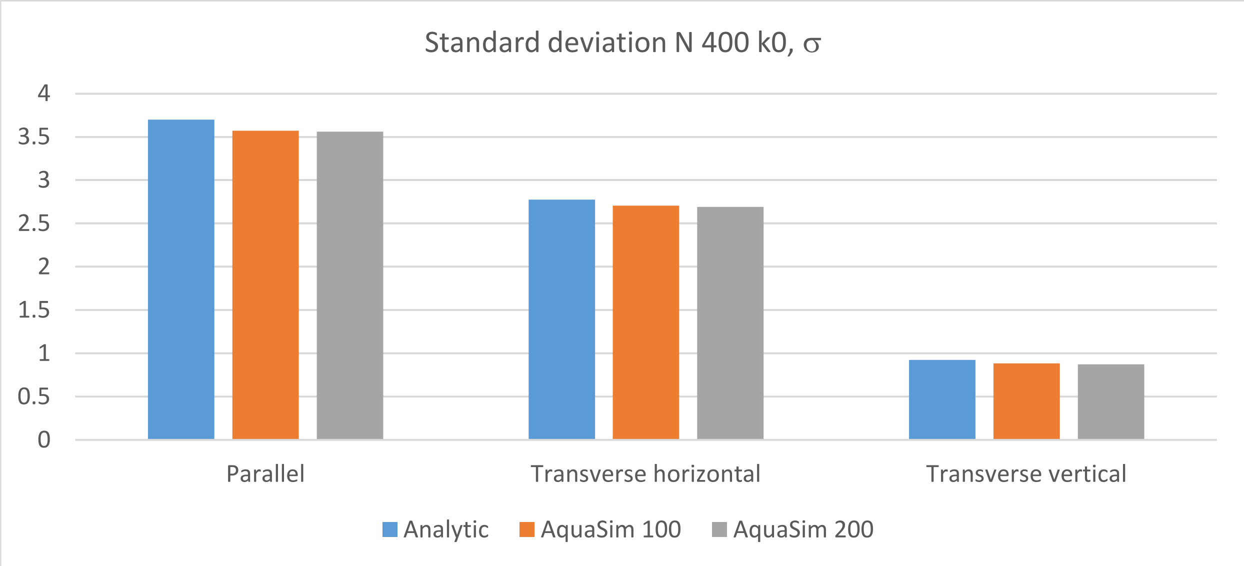

Figure 6 Standard deviations analytic results compared to finite representation

As seen from Figure 6 the results compare well also for transverse gust components. Using NORSOK, transverse gust components are not included. The vertical gust has relatively more energy at low periods such that for this gust component, the cut-off of the periods lower than 0.1 sec is of some importance.

It should be noted that when using the wind load formulation in AquaSim, the wind loads should first be introduced to a simplified model as a check, to ensure that the wind loads are credible. Then a more complex model should be assessed.

5. REFERENCES

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